Modelling and Simulation of Impulse Voltage Generator using Marx Circuit

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By

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CERTIFCATE

This is to certify that the thesis designated, "**Modelling and Simulation of Impulse Voltage Generator using Marx Circuit** "submitted by Jolly Mondal in partial attainment of the essentials for the honor of Bachelor of Technology Degree in Electrical Engineering at the National Institute of Technology, Rourkela is a genuine work carried out by her under my instruction and guidance.

To the best of my knowledge, the matter exhibited in the thesis has not been submitted to any other university/institute for the award of any Degree or Diploma.

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CONTENTS

ABSTRACT

Protection of power system is an important aspect for the continued service of the electrical power system. Mostly the protection of electrical power depends on the performance of insulation systems under transient over voltage conditions arises due to lightening and switching applications. Transient over voltages in addition to the abrupt changes in the state of power systems, e.g. switching operations or faults are known as switching impulse voltages and that due to lightening are known as lightening impulse voltages. Very short pulse high-voltage or high-current surges can be produced by an electrical apparatus known as impulse generator. High impulse voltages are used to test the durability of electric power equipment against lightning and switching surges. The Marx Impulse generator is used to generate such high impulse voltages. This generator consists of multiple capacitors that are first charged in parallel through charging resistors by a high-voltage, direct-current source and then connected in series and discharged through a test object by a concurrent spark-over between the sphere gaps. A total of eight stages of both Standard as well as Improved Marx Impulse generator were designed and the impulse waves were recorded. These recorded impulse waves were compared with the standard impulse wave with front time of 1.2µ seconds and fall time of 50µ seconds. The energy and efficiency of all the stages were calculated and the percentage of error in the rise time and fall time was also found out. The simulation was done with the help of NI Multisim Software Package. A small practical prototype of second stage of Standard Marx Impulse Generator circuit was also designed for a voltage source of 12 V and its output impulse wave was compared with that of the standard impulse wave. In this work, the whole circuit was modelled, simulated and practically designed in two different parts i.e. the rectifier circuit and the impulse voltage generating circuit. The effects of the circuit parameters on the impulse wave characteristics were also studied.

LIST OF FIGURES

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LIST OF SYMBOLS

Symbols	Symbols Name
C1, C3, C4, C5	Charging Capacitors
C2	Discharging capacitors/Test Object
R1, R2	Wave shaping resistors
T_1	Rise Time
T_2	Fall Time
V_p	Peak output voltage
V_o	Applied direct current voltage
n	Number of stage
α	Wave tail time constant
β	Wave rise time constant

CHAPTER 1

Introduction

Introduction

Introduction to NI Multisim

Objective

Organisation of thesis

CHAPTER 1

INTRODUCTION

1.1 Introduction

Power systems equipment must tolerate not only the rated voltage which corresponds to the highest voltage of a particular system, but also over voltages. Accordingly, it is mandatory to test high voltage (HV) apparatus during its development stage. Protection of power system is an important aspect for the continued service of the electrical power system [1-4]. Mostly the protection of electrical power depends on the performance of insulation systems under transient over voltage conditions arises due to lightening and switching applications. Transient over voltages along with the abrupt changes in the state of power systems, e.g. switching operations or faults are known as switching impulse voltages and that due to lightening are known as lightening impulse voltages. It has become generally identified that switching impulse voltages are usually the prevalent factor affecting the design of insulation in HV power systems for rated voltages of about 300 kV and above [5-6]. Hence attention is required for these two types of over voltages.

The Marx Impulse generator is used to generate lightening impulse voltage. The magnitude and nature of test voltage varies with the rated voltage of particular equipment. The generated voltage from impulse generator must satisfy the standard values of voltage defined by the International Electro Techno Commission in order to qualify as a standard impulse voltage that can be used for testing purposes [7]. The standard methods of measurement of high-voltage and the basic methods for application to all types of apparatus for alternating voltages, direct voltages, switching impulse voltages and lightning impulse voltages are laid down in the important national and international standards. Although the wave shapes of impulse voltages occurring in the system may vary extensively. The standard waveform of a lightening impulse wave is 1.2/50µ seconds [5-7].

The entire impulse generator system has two parts. The first part produces dc voltage through a rectifier circuit in particular a voltage multiplier circuit and the second part is the Marx circuit and using these two parts the lightening impulse voltage is obtained as an output from the Marx Topology.

1.2 Introduction to NI Multisim

National Instruments (NI) Multisim, an electronic illustrative capture as well as a simulation program which is part of circuit scheme programs, along with NI Ultiboard. It is generally used in academia and industry for SPICE simulation, graphic design and circuit simulation.
This circuit design programs use the original Berkeley SPICE based software simulation. A company named Electronics Workbench first developed Multisim formally. It is now a part of National Instruments [8].It assimilates both import and export features to the Printed Circuit Board layout software in the NI Circuit design suite. Microcontroller simulation is included in Multisim. It is generally used as educational tool for teaching electronic experts and electronic engineering curriculum in institutes and universities. NI has secured this educational tradition with a specific version of Multisim features developed for training electronics.

1.3 Objective

Over voltages on power lines create a great danger for the equipment, continuity of supply and more specifically the safety of personnel. Hence research in this area specifically the study of Impulse waves, its generation, its nature and characteristics is desired. As the power lines and equipments are exposed to the atmosphere, hence lightening strike is a common phenomenon. The main complication in high voltage engineering is the construction of proper high voltage insulation with minimum dimension at low cost. The only way to protect the power systems is to test the equipment's insulation strength by subjecting them to high impulse voltages and accordingly design the insulation of these equipments. Therefore, prediction of impulse withstands voltage for power equipments are very much essential which can only be achieved if we closely monitor the generation and characteristics of impulse waves. This motivates the need for practical high voltage impulse generation using Marx Impulse generator. Marx generators are used to provide very high voltage pulses for the examining the strength of insulation of electrical equipments such as large power transformers, or insulators used for aiding power transmission lines.

The main objective of the thesis is:

- To develop Standard and Improved Marx Generator circuit using Multisim software to generate an impulse voltage.

- To develop a practical circuit model of Marx Generator and to produce an impulse voltage.
- The final goal is to compare the theoretical values of front time, tail time and peak voltage obtained in simulation with those recorded in practical circuit.

1.4 Organisation of Thesis

This thesis is classified into six chapters.

Chapter 1: This chapter deals with the introduction part of the project. It concentrates on the generation, nature and characteristics of impulse waves and use of Multisim in high voltage Engineering.

Chapter 2: This chapter deals with background and literature review of impulse voltage. It focuses on different types of impulse generation circuits (Standard and Modified Marx generator) used for generating impulse waves, characteristics of impulse wave.

Chapter 3: This chapter deals with methodology used in producing the impulse wave i.e. calculation of front and tail resistors, calculation of charging and discharging capacitors for both Standard and Modified Marx generator.

Chapter 4: This chapter deals with the results obtained from simulation and calculation of front and tail time, error calculation, energy and efficiency calculation of both the circuits and comparison of the waveforms obtained in both the cases.

Chapter 5: This chapter deals with the practical circuit setup and the results obtained from it. It also includes the comparison between the simulated circuit results and the practical circuit results.

Chapter 6: This chapter involves the conclusion and summary part.

CHAPTER 2

Background and Literature Review

Literature review

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 Literature review

High voltage technology was introduced at the beginning of the last century for electrical power generation and transmission systems. Long before that efforts have been made to study the lightening characteristics inside laboratory to carry out the tests on power system equipment in order to protect them from hazardous of lightening strike. A number of theories on lightening formation and generation have been presented [5-8]. Since the exploration on lightening started, efforts have been made to realise the lightening phenomenon inside laboratory so that the characteristics of the lightening can be studied more accurately and tests on power system equipment can be carried out. Many authors have presented their work about the generation of lightening impulse inside laboratory [3-15]. Marx has been the important guiding principle in generating lightening impulse voltage [16-20]. Almost in every paper Marx theory has been used but some paper have modelled the same principle differently for different application. Modified Marx generator has also been studied extensively [20-21]. In almost all the papers discussed so far has employed capacitive loading for getting the impulse responses. Marx circuit has been widely used in the generation of high repetition voltage pulses, high power microwaves where rise time ranges in the ns region. For accurate measurement of high voltage pulses through measuring instruments, measurement techniques and procedures have also been proposed [4], [19].

2.1.1 Single Stage Standard Marx impulse Circuit

The energy storage capacitor, C1, is charged from the high voltage direct current (HVDC) power supply. The output waveform is controlled by the interaction of the front resistor R1 and the tail resistor R2 with the energy storage capacitor C1 and the load C2. The sphere gap in the circuit is a voltage limiting or voltage sensitive switch. Capacitor C1 charges from a dc source until the sphere gap breaks down. The time of breaking down of sphere gap is very short.

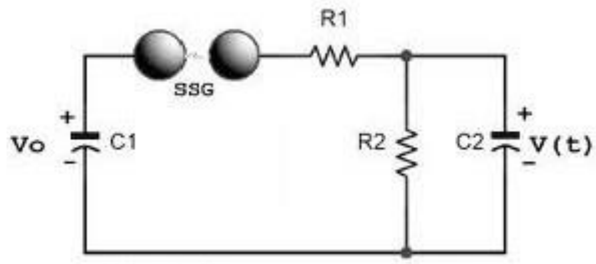

Figure 2.1: Single Stage Impulse Generator Circuit (Standard Marx circuit)

Charging voltage in large impulse generator can be of the order of mega volt (MV). The wave shaping network in the impulse generator consists of R1, R2 and C1. Resistor R1 basically damps the circuit and regulates the front time while R2 is the discharging resistor through which C1 will discharge. C2 is the load which represents the capacitance of the load itself and capacitance of other elements parallel with the load. Capacitor C1 discharges into the circuit comprising of R1, R2 and C2, when break down of the sphere gap takes place [5].

Usually the impulse generator incorporates a load capacitance which is adequately large that the output waveform shape does not change considerably with changes in sample capacitance. The resistors R1, R2 and the capacitance C2 form the wave shaping network. R1 will primarily damp the circuit and control the front time T1. R2 will discharge the capacitors and therefore essentially control the wave tail. The capacitance C2 represents the full load, i.e. the object under test as well as all other capacitive elements which are in parallel to the test object [1], [2].

Fast impulse or slower impulses can be generated if switching modifications are applied in the impulse generating circuits. One probable way of generating longer pulse is to add an inductance in series with R1 [5], [7]. The difference in circuit arrangement will have different efficiency for the impulse generator. The dc voltage can be generated by the use of rectifier circuits. The rectifier used in the simulation is full wave rectifier circuit. The smoothness of dc value is not much of concern as it has to only charge the capacitor to peak. A sphere gap is a switch and the voltage across the sphere gap builds up as a voltage building up across capacitor takes place. Normally the sphere gaps are allowed to fire naturally or for smooth operation it can be fired through control methods.

2.1.2 Multi Stage Standard Marx Impulse Circuit

Due to the difficulties faced in very high voltage switching of the spark gap, increase in circuit element size, requirement of high direct current voltage to charge capacitor and difficulties in corona discharge suppression from the structures during charging period the extension of the single stage to multistage impulse generator is made [5-7].

A multistage generator is developed by cascading smaller single stage generator to generate high magnitude of output voltage. The primary requirement is to charge capacitors through the rectifier circuit and when all the capacitor reaches to the fully charged state then spark gaps are allowed to break down causing the capacitors to add in series. As a result the nominal output voltage is equal to the input voltage multiplied by the number of stages in the impulse generator circuit. At first, n capacitors are charged in parallel to a voltage (V) by a high voltage DC power supply through the resistors. The spark gaps used as switches have the voltage V across them, but the gaps have a breakdown voltage greater than V, so they all behave as open circuits while the capacitors charge. The last gap isolates the output of the generator from the load; without that gap, the load would prevent the capacitors from charging [1-3]. To create the output pulse, the first spark gap is caused to break down (triggered); the breakdown effectively shorts the gap, placing the first two capacitors in series, applying a voltage of about 2V across the second spark gap. Consequently, the second gap breaks down to add the third capacitor to the stack, and the process continues to sequentially break down all of the gaps. The last gap connects the output of the series stack of capacitors to the load. Ideally, the output voltage will be nV, the number of capacitors times the charging voltage, but in practice the value is less.

2.1.3 Single stage Improved Impulse Marx Circuit

The Improved Impulse Marx generator works same as the standard Impulse Marx generator i.e. the energy storage capacitor, C1, is charged from the high voltage direct current (HVDC) power supply. The output waveform is controlled by the interaction of the front resistor R1 and the tail resistor R2 with the energy storage capacitor C1 and the load C2. The only difference is that the switch here acts as a potential divider that divides the tail resistor. The advantage of this method is that this circuit design helps in proper shaping of the impulse wave as the standard wave i.e. it helps in reducing the errors in rise time and tail time. The rise in peak voltage is not that considerable.

2.1.4 Multi Stage Improved Impulse Marx Circuit

In multistage Marx generator circuit resistive voltage divider are used in order to minimize the level of voltage to a measureable value across each capacitor.[5],[6] It consists of two impedances which are connected in series and a tapping is introduced in between these resistors in order to connect the sphere gap. Usually charging resistance is chosen to limit the charging current to about 50 to 100mA, while the generator capacitance is chosen such that the product of charging resistance and generator capacitance is about to 10s to 1 minute [4]. The discharge time constant will be too small (microseconds), compared to the charging time constant which will be few seconds. For designing the circuit of Marx Impulse Generator various equations were used. The standard impulse wave was calculated using

$$V = Vo[e^{-\alpha t}\text{-}e^{-\beta t}] \quad \text{.......} \quad (1)$$

Where, α and β are constants of microsecond values. V_o is the applied DC voltage. The efficiency of each stage was given by

$$\text{Efficiency} = \frac{Vp}{Vo} \quad \text{.......} \quad (2)$$

Where, V_p is the peak output voltage; V_o is the applied DC voltage. It can also be given by

$$\text{Efficiency} = (1/(1+(C2 \times n)C1)) \times (1/(1+\left(\frac{R1}{R2}\right)) \quad \text{.......} \quad (3)$$

Where, $C1, C2$ are charging and discharging capacitors, $R1$, $R2$ Are front and tail resistors and n is the number of stage. And the energy stored was calculated using

$$W = ((\frac{C1}{n}) * Vo * Vo)/2 \quad \text{.......} \quad (4)$$

Where, $C1$ is the charging capacitor; V_o is the applied DC voltage and n is the number of stage [5], [6].

In practice all the capacitors are not charged to the same value due to the presence of series resistance in the circuit. In theory any desired output voltage can be obtained simply by increasing the number of stages. But in practise the effect of series resistance between the source and distant capacitor limits the voltage obtainable. Therefore we can go for an optimum number of stages for the generation of high impulse voltages through impulse generator circuit.

2.1.5 Standard Impulse waveform

The induced overvoltage in power system are characterised by their shapes, magnitudes, time periods and frequency of occurrence. Two types of overvoltage normally prevail in power system which takes the system to unstable stage. The unstable condition arises when the peak amplitude of the nominal operating voltage exceeds. The induced Transient over voltages caused by lightening and switching surges causes steep build up voltages on transmission line and other equipment. Experimental records show that these waves have a rising time of 0.5 μsec to 10 μsec and decay 50% of the peak value of the order of 30μsec to 200 μsec. The wave shapes are arbitrary and unidirectional. The standard wave rise time and fall time for a lightening impulse wave is 1.2μsec and 50μsec respectively [5], [6], [20].

The kind of wave shape related with the lightening impulse voltage is given by the equation (1) where α and β are constants in the range of microseconds and Vo is the charging voltage.

$$V = Vo[e^{-\alpha t}\text{-}e^{-\beta t}] \qquad (1)$$

This equation explains that lightning is a doubly exponential curve which rises quickly to the peak and falls relatively slow to zero values. Impulse voltages are defined in terms of their time periods i.e. rise time, fall time and also the peak voltage.

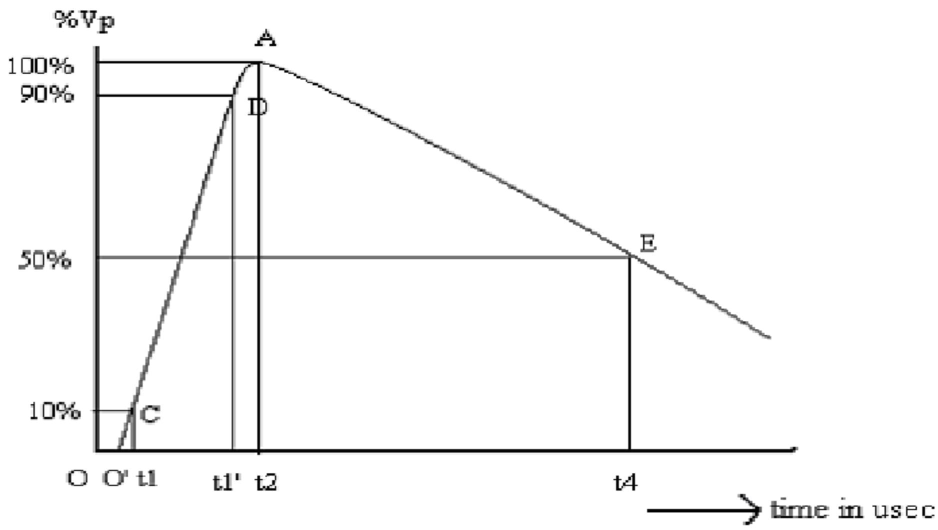

Figure2.2: Standard Impulse wave

The rise time is defined as the time taken for the impulse to rise from 10% of peak value to 90% of peak value and the tail time is defined as the time taken for the impulse to drop to 50% of the peak value. Now as shown in Figure 2.2 the rise time is given by O’t1’ and fall time by O’t4.

CHAPTER 3

Methodology used for determining Marx circuit parameters

Analysis of single stage Standard Marx circuit

Determination of Circuit elements

CHAPTER 3

METHODOLOGY USED FOR DETERMINING CIRCUIT PARAMETERS

3.1 Analysis of single stage Standard Marx circuit

For the determination of circuit elements the analysis of circuit given in Figure 2.1 is required. Laplace transformation is essential for this analysis. For the circuit given in Figure 2.1 the output voltage is given by the expression

$$V(s) = \left(\frac{V_0}{s}\right) \times \left(\frac{Z_2}{Z_1+Z_2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

Where $Z_1 = \left(\frac{1}{C1(s)}\right) + R1$ and $Z_2 = \left(\frac{R2}{C2(s)}\right)/(R2 + \left(\frac{1}{C2(s)}\right)$ and after substituting in the above equation (5) we get

$$V(s) = \left(\frac{V_0}{k}\right) \times \left(\frac{1}{s^2+as+b}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(6)}$$

Where$a = \left(\frac{1}{R1C1}\right) + \left(\frac{1}{R1C2}\right) + \left(\frac{1}{R2C2}\right)$; $b = \left(\frac{1}{R1R2C1C2}\right)$ and $k = R1C2$. For this circuit we obtain the time domain expression from the transform table and we obtain the following expression

$$V(t) = \left(\frac{V_o}{k}\right) \times \left(\frac{1}{\alpha_2-\alpha_1}\right) \times \left(e^{(-\alpha_1 t)} - e^{(-\alpha_2 t)}\right) \ldots. \text{(7)}$$

Where α_1 and α_2 are the roots of the equation $s^2 + as + b = 0$ or it is given by

$$\alpha_1, \alpha_2 = \left(\frac{a}{2}\right) \mp \sqrt{\left(\left(\frac{a}{2}\right)^2 - b\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(8)}$$

3.2 Determination of Circuit elements

The basic job is to find the resistor values for R1 and R2, as C2 and C1 are known in general. For larger generators the discharge capacitors are always provided and dimensioned for a good efficiency within a certain range of C2. This total load capacitance can be easily measured if it is not known in advance. The unknown resistance values can then be calculated by using the equation given below

$$R1 = \left(\frac{1}{2C1}\right) [\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right) - \sqrt{\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right)^2 - \left(\frac{4(C1+C2)}{(\alpha_1 \alpha_2 C2)}\right)}] \text{............ (9)}$$

$$R1 = \left(\frac{1}{2(C1+C2)}\right) \left[\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right) - \sqrt{\left(\left(\frac{1}{\alpha_1}\right) + \left(\frac{1}{\alpha_2}\right)\right)^2 - \left(\frac{4(C1+C2)}{(\alpha_1 \alpha_2 C2)}\right)}\right] \text{... (10)}$$

The above two equations contain the time constants $1/\alpha_1$ and$1/\alpha_2$, which depend upon the wave shape. There is, however no simple relationship between these two time constants and the times T_1 and T_2 as defined in the national or international recommendations. This relationship can be determined by implementing the definitions to the analytical expressions for$V(t)$. This relationship is irrational and must be computed numerically. The following table shows the result for some selected wave shapes.

TABLE-I

RELATIONSHIP BETWEEN RISE TIME, FALL TIME AND TIME CONSTANTS [5]

T_1/T_2	$1/\alpha_1$	$1/\alpha_2$
1.2/5	3.480	0.800
1.2/50	68.20	0.405
1.2/200	284.0	0.381
250/2500	2877	104.0

We are dealing with impulse waves having rise time of 1.2µseconds and fall time 50µseconds. So by considering the above drawn table the time constants to be used for determining the circuit elements are 68.20 and 0.405.

The following approximate analysis is used to calculate the wave front time T_1 and the wave tail time and T_2. The resistance R2 is very large. Hence, time taken for charging is approximately three times the time constant of the circuit and is given by the formula given below.

$$T_1=3R1Ce \quad \text{...} \quad (11)$$

Here C_e is given by the following equation

$$C_e=(C1 \times C2)/(C1+C2) \text{................................} \quad (12)$$

R1Ce is the charging time constant in micro-second. For discharging or tail time, the time for 50% discharge is approximately given below.

$$T_2=0.7 \times (C1 + C2) \times (R1 + R2) \text{ ....} \quad (13)$$

With approximate formulae, the wave front and wave tail resistances can be estimated to within the error limits for the standard impulse waves. The equations used to calculate these are

$$R1=(T_1 \times (C1 + C2))/(3 \times (C1 \text{................} \quad (14)$$

$$R2 = \left(\frac{T_1}{0.7 \times (C1+C2)}\right) - R1 \quad \text{........................} \quad (15)$$

The $C1/C2$ ratio was taken 20 and accordingly the values of front and tail resistors were calculated for each stage by substituting the values of time constants in equations (9) and (10). Now for the improved Marx circuit the same procedure is followed only the difference being the charging, front and tail resistors are divided by the specific stage number it is dealing with. In practise the Marx circuit is used in modified form explained above with the resistive voltage dividers placed in parallel to the test object. Their resistor value may contribute to discharge the circuits. Using the above equations and procedure the design parameters of 8 stages were calculated and were simulated with the help of Multisim. The values used in each stage of impulse generator are given below in tabular form.

TABLE-II

DESIGN PARAMETERS FOR STANDARD AND IMPROVED MARX CIRCUIT

Stage	Standard Impulse R1(Ω)	Marx Circuit R2(Ω)	Improved Impulse R1(Ω)	Marx Circuit R2(Ω)
1st	0.84	05.9600	0.2469	1.3982
2nd	0.88	012.107	0.1100	1.5130
3rd	0.92	17.7135	0.7660	1.4767
4th	0.96	22.8500	0.0600	1.4275
5th	1.00	27.5700	0.0500	1.3784
6th	1.04	31.9270	0.0430	1.3300
7th	1.08	35.9570	0.0380	1.2800
8th	1.12	39.6960	0.0350	1.2400

The standardised nominal values of rise time and fall time are difficult to achieve in practise, as even for fixed values of C1 the load C2 will vary and the exact values for R1 and R2 according to equations (9) and (10) are in general not available. These resistors have to be dimensioned for the rated high voltage of the generator and are accordingly expensive. The permissible tolerances for rise time and fall time are therefore necessary and used to graduate the resistor values. A recording of the real output voltage $V(t)$ will in addition be necessary if the admissible impulse shape has to be testified.

CHAPTER 4

Simulation Results

Marx Impulse Generator
Front time, tail time and Error Calculation
Energy and Efficiency Calculation
Comparison of the waveforms obtained from Standard Marx Circuit
and Improved Marx Circuit

CHAPTER 4

SIMULATION RESUTLS

4.1 Marx Impulse Generator

4.1.1 Standard Marx Impulse Generator

The basic circuit used for generation of impulse wave is shown in Figure 2.1. The sphere gap in the circuit is a voltage limiting or voltage sensitive switch. Capacitor C1 charges from a dc source until the sphere gap breaks down. The time of breaking down of sphere gap is very short. Charging voltage in large impulse generator can be of the order of mega volt (MV). The wave shaping network in the impulse generator consists of R1, R2 and C1. Resistor R1 basically damps the circuit and regulates the front time while R2 is the discharging resistor through which C1 will discharge. C2 is the load which represents the capacitance of the load itself and capacitance of other elements parallel with the load. Capacitor C1 discharges into the circuit comprising of R1, R2 and C2, when break down of the sphere gap takes place.

The circuit setup for simulation of first stage of Standard Impulse Generator is shown below:

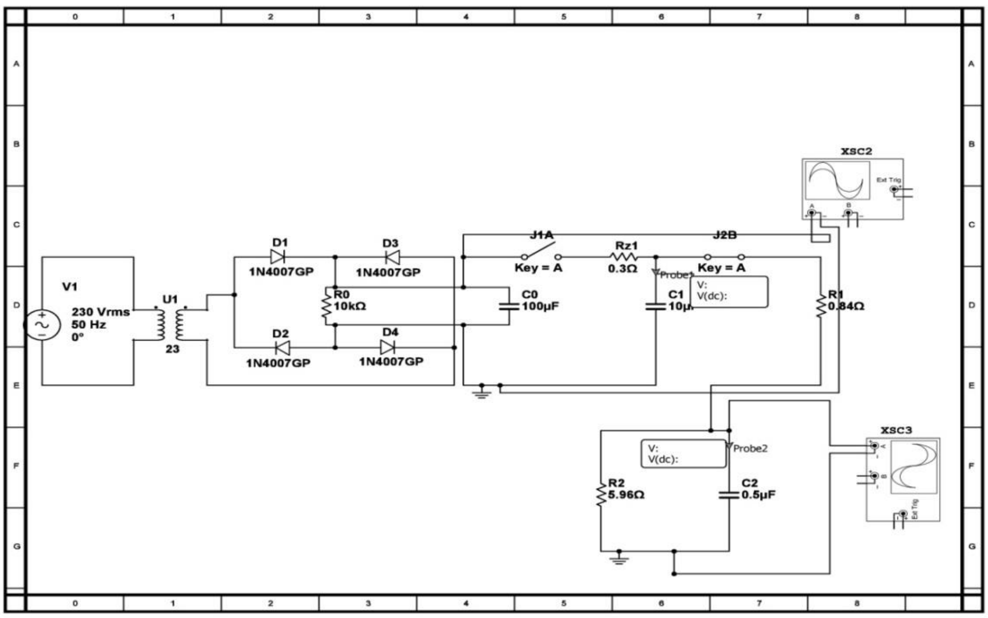

Figure 4.1: Schematic Diagram of Single Stage Standard Marx Impulse Voltage Generator

Fast impulse or slower impulses can be generated if switching modifications are applied in the impulse generating circuits. One probable way of generating longer pulse is to add an inductance in series with R1. The difference in circuit arrangement will have different efficiency for the impulse generator. The dc voltage can be generated by the use of rectifier circuits. The rectifier used in the simulation is full wave rectifier circuit. The smoothness of dc value is not much of concern as it has to only charge the capacitor to peak. A sphere gap is a switch and the voltage across the sphere gap builds up as a voltage building up across capacitor takes place. Normally the sphere gaps are allowed to fire naturally or for smooth operation it can be fired through control methods.

Standard impulse wave for the first stage using the Standard Marx Impulse generator is shown below.

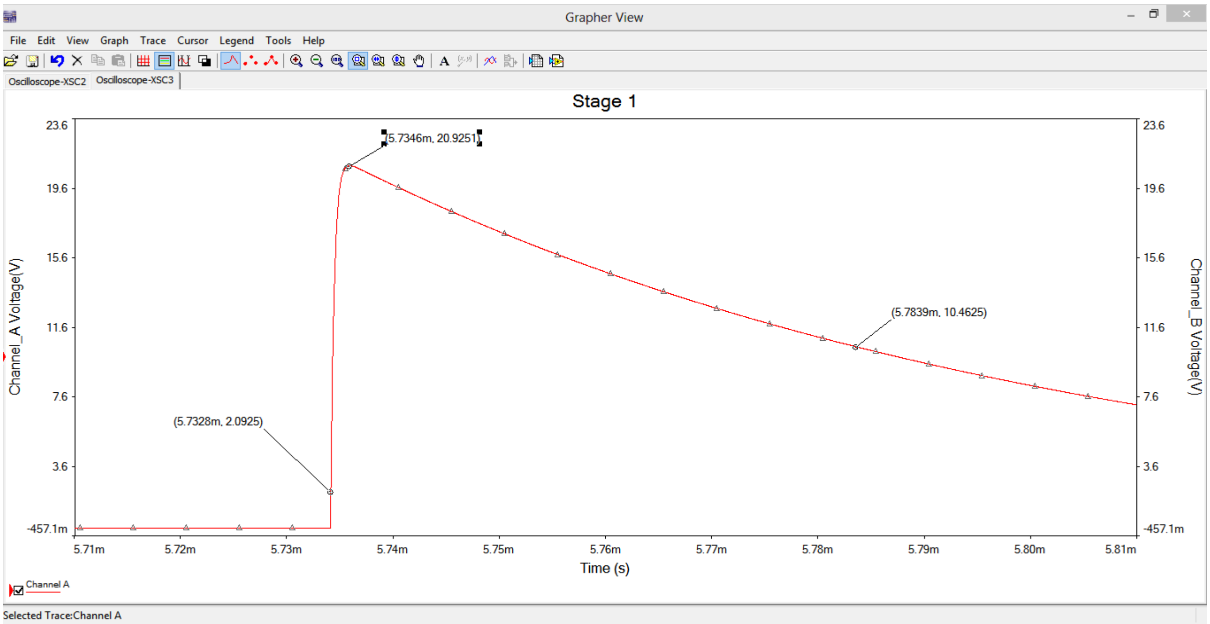

Figure 4.2: A standard impulse wave (stage 1 using Standard Marx impulse voltage circuit)

In the first stage the dc charging voltage supplied was around 20V and as shown in the Figure 4.2 the Marx Impulse Generator produces an output impulse wave with a peak of 20.9251V. The output value is obtained as a result of discharging of the fully charged capacitor through R1 and R2. The discharge phenomenon occurs when the switch is triggered. Now the output voltage is more than the charging voltage which is acceptable. The graph also points the time at which 10%, 50% and 90% of the peak value is reached.

The output waveforms of second, third and fourth stage of Standard Marx impulse generator with their peaks indicated on the graph is shown below.

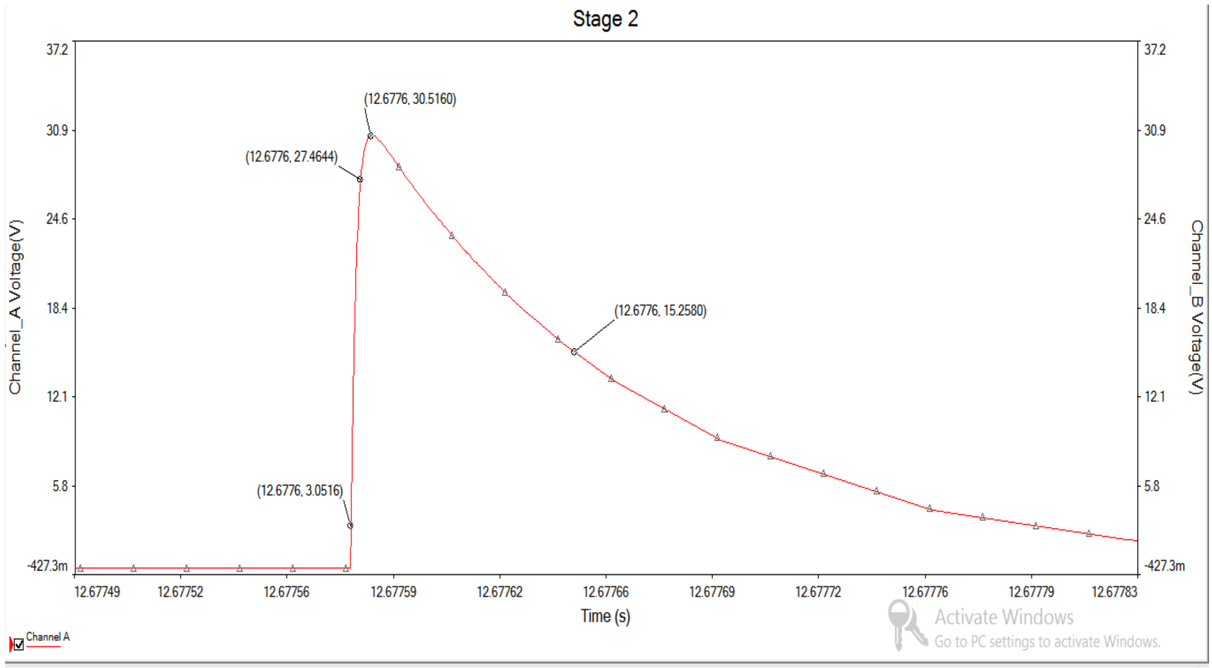

Figure 4.3: A standard impulse wave (stage 2 using Standard Marx Impulse voltage circuit)

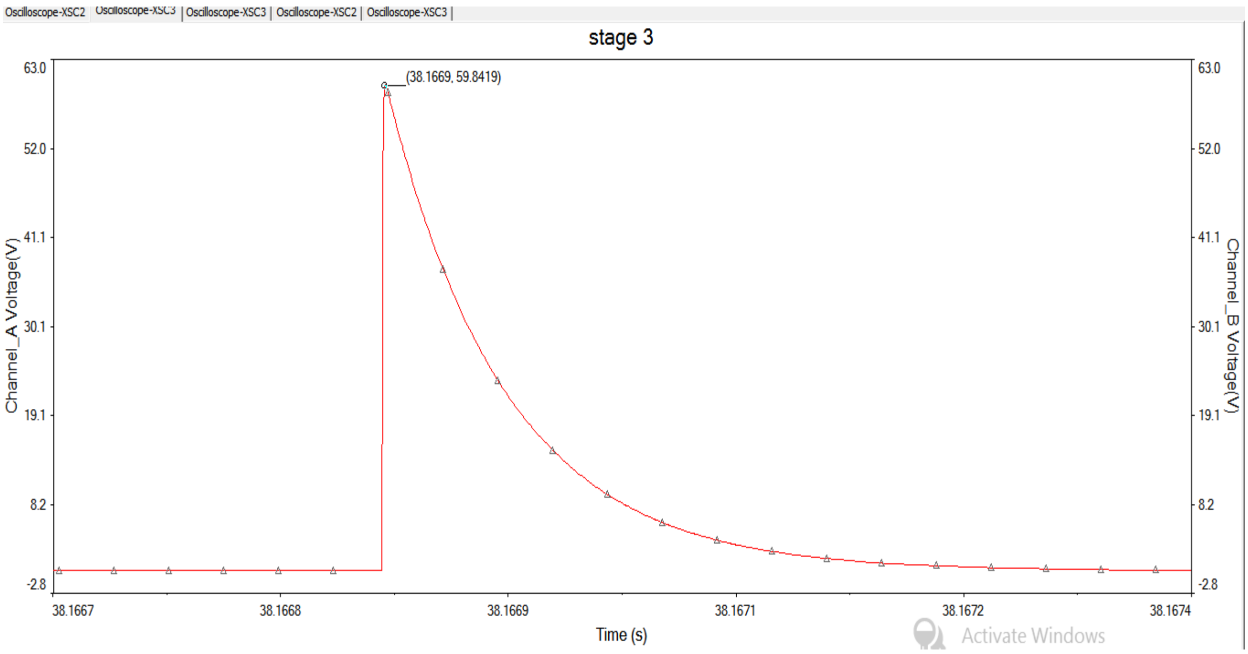

Figure 4.4: A standard impulse wave (stage 3 using Standard Marx Circuit)

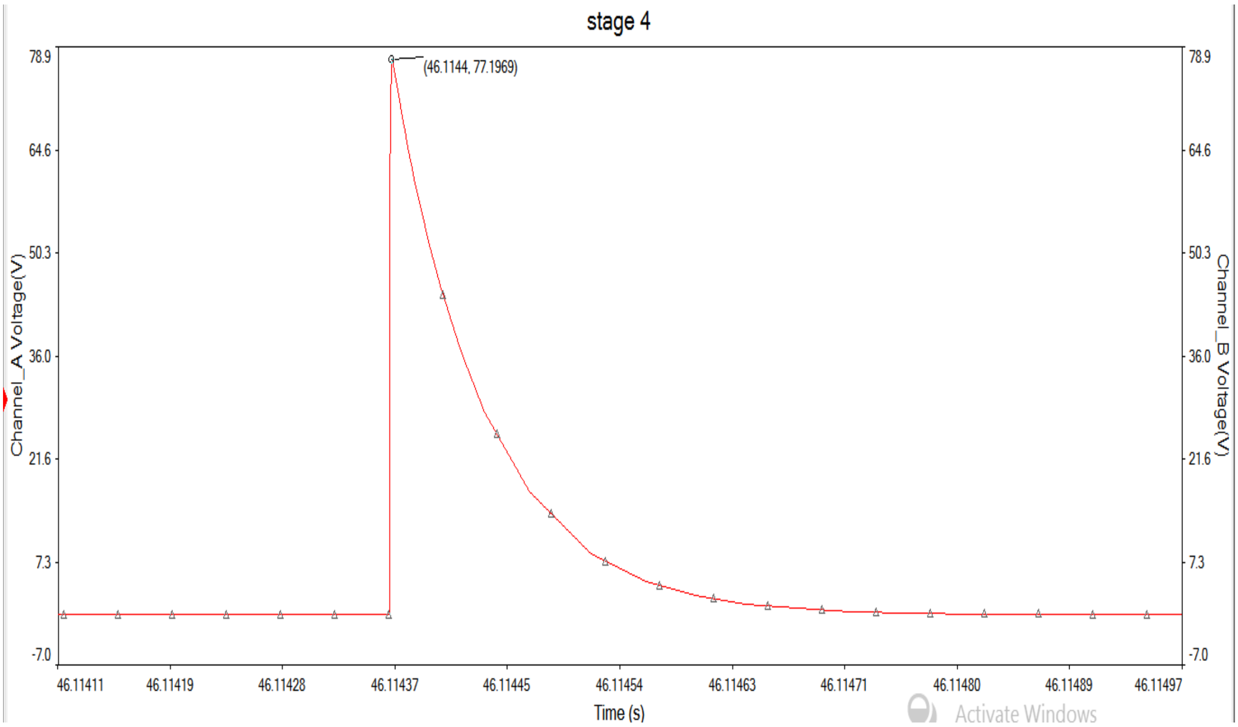

Figure 4.5: A standard impulse wave (stage 4 using Standard Marx Impulse voltage circuit)

4.1.2: Improved Marx Impulse Generator

In Improved Marx circuit voltage dividers are used in order to minimise the value of voltage to a measurable value across each capacitor. It consists of two impedances which are connected in series and a tapping is imported in between these resistors in order to connect the sphere gaps. Wave shaping resistors are divided into two groups known as damping resistors and discharging resistors. Damping resistors control the shape of the impulse voltage during rise time where as discharging resistors control the shape of the impulse wave during fall time. Test object is a capacitor whose value is always less than that of charging capacitor. The improved Marx impulse generator works same as that of standard Marx impulse generator the difference lies on the charging and discharging time. Here the sphere gap acts like a voltage divider which divides the tail resistors and hence the RC constant of the circuit changes which further results in the differences in the rise time and tail time.

The first stage of Improved Marx Impulse Generator setup is shown below:

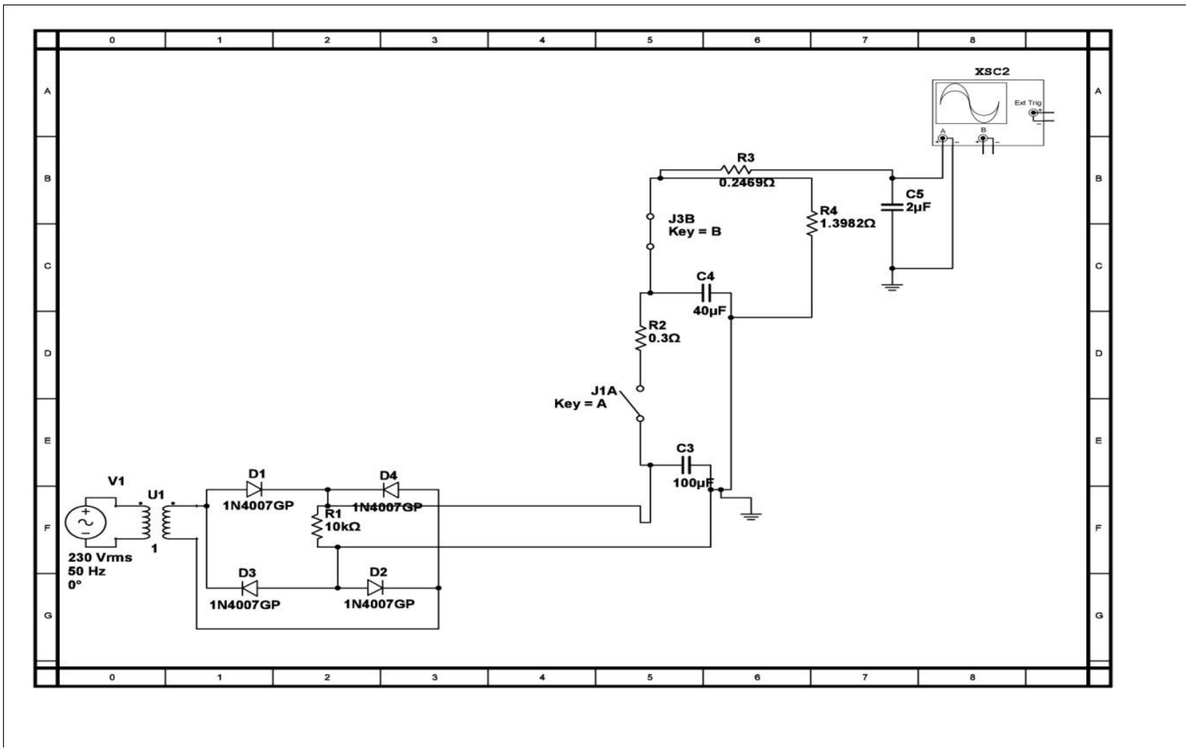

Figure 4.6: Schematic Diagram of Single Stage Improved Marx Impulse Voltage Generator

Similar to the Standard Marx impulse generator for fast impulse or slower impulses, switching modifications are applied in the impulse generating circuits. One probable way of generating longer pulse is to add an inductance in series with R1. The difference in circuit arrangement will have different efficiency for the impulse generator. The dc voltage can be generated by the use of rectifier circuits. The rectifier used in the simulation is used same as in Standard Marx impulse generator i.e. full wave rectifier circuit.

The impulse waveforms obtained from Improved Marx circuit for the first stage has been shown below.

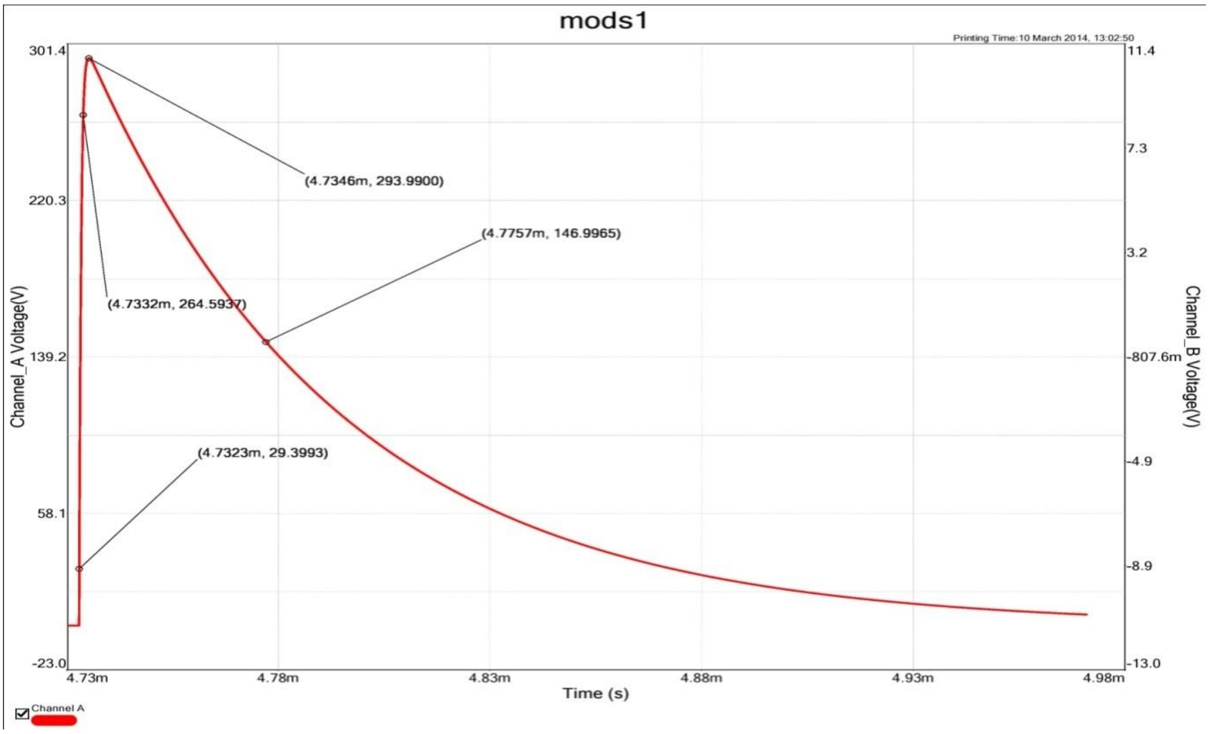

Figure 4.7: A standard impulse wave (stage 1 using Improved Marx Impulse voltage circuit)

In the first stage the dc charging voltage supplied was around 230V and as shown in the Figure 4.2 the Marx Impulse Generator produces an output impulse wave with a peak of 233.99V. The output value is obtained as a result of discharging of the fully charged capacitor through R1 and R2. The discharge phenomenon occurs when the switch is triggered. Now the output voltage is much more than the charging voltage. The graph also points the time at which 10%, 50% and 90% of the peak value is reached.

The output waveforms of second, third and fourth stage of Standard Marx impulse generator with their peaks indicated on the graph is shown below.

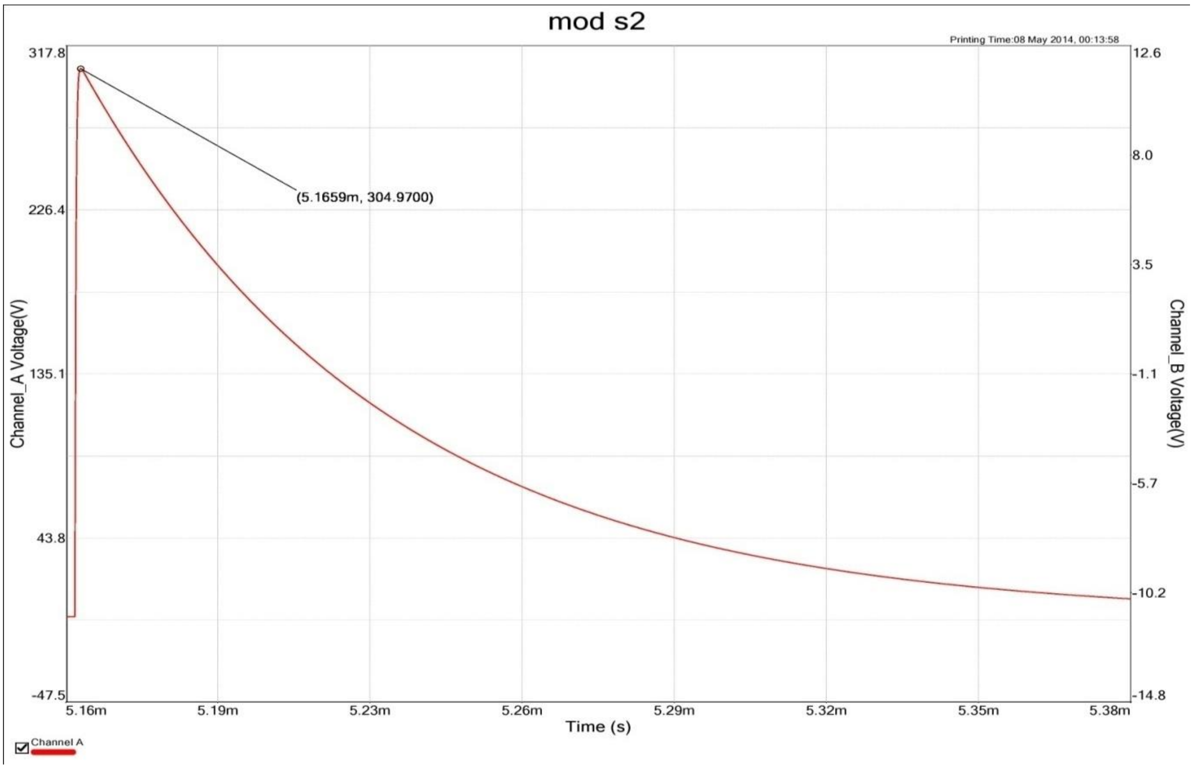

Figure 4.8: A standard impulse wave (stage 2 using Improved Marx Impulse voltage circuit)

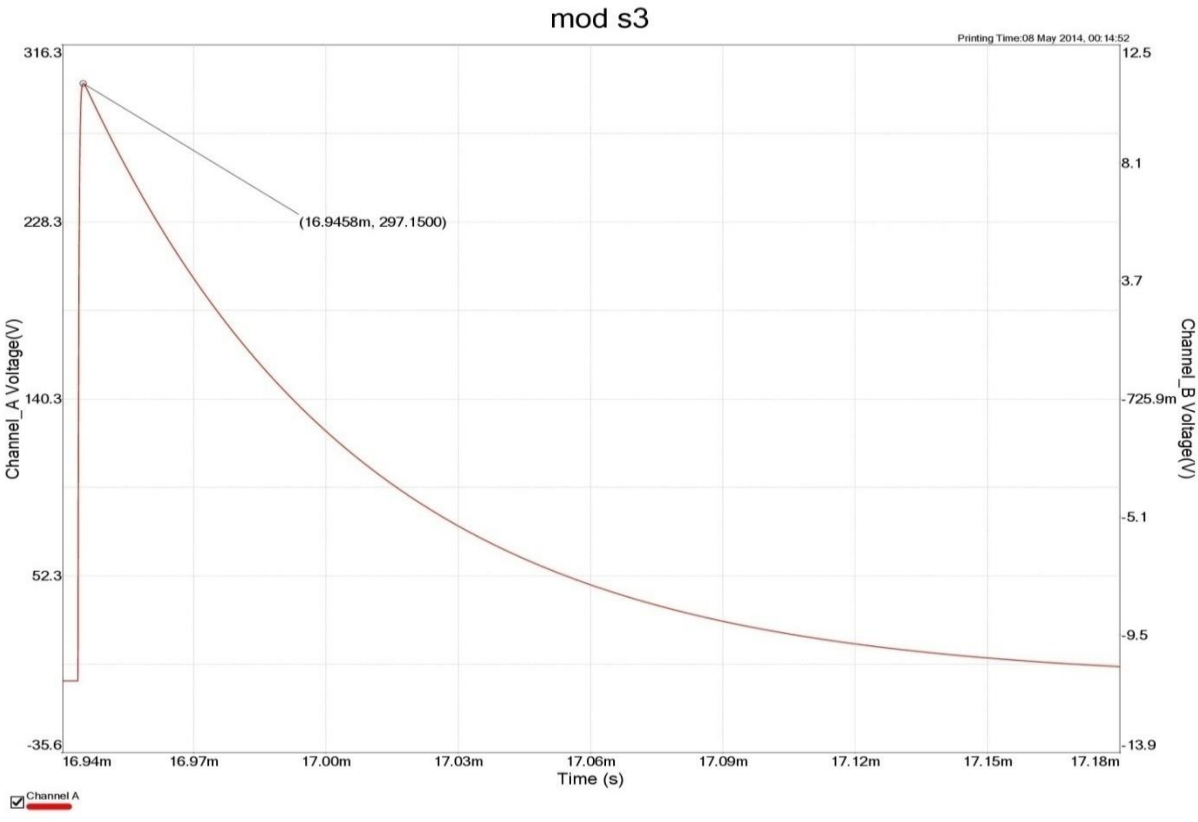

Figure 4.9: A standard impulse wave (stage 3 using Improved Marx Impulse voltage circuit)

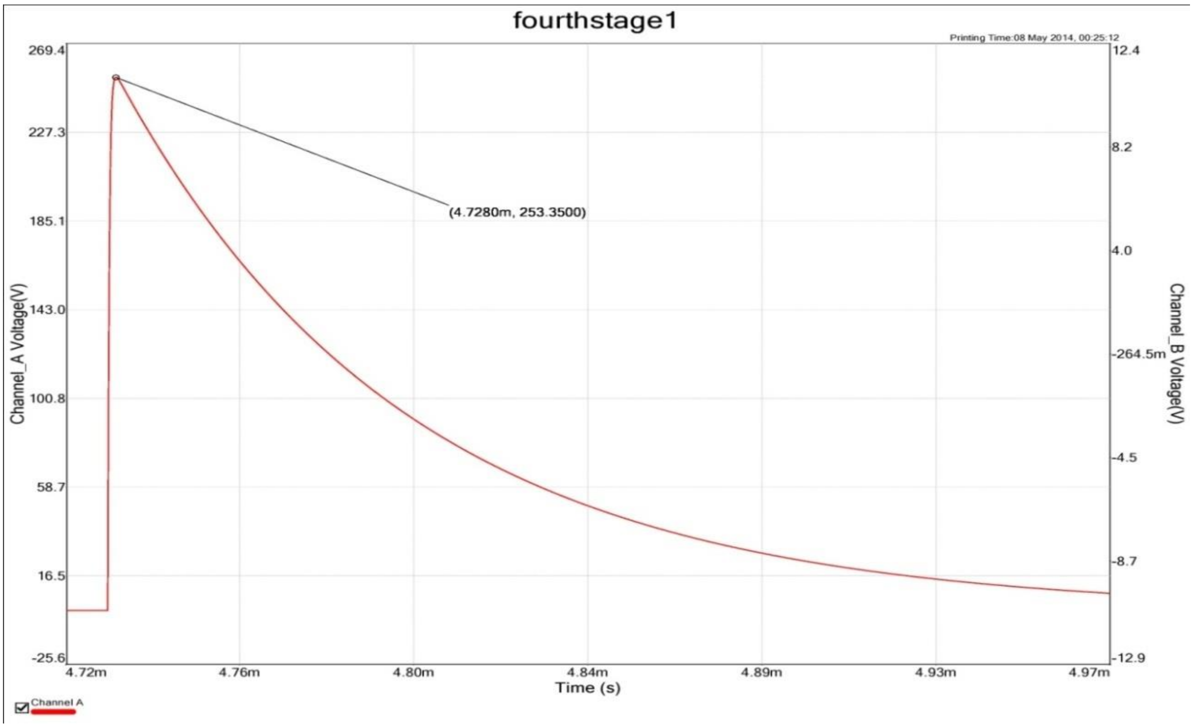

Figure 4.10: A standard impulse wave (stage 4 using Improved Marx Impulse voltage circuit)

4.2: Front time, tail time and Error Calculation

Rise time is 1.25 times of difference between the time taken to reach 90% of peak impulse voltage and time taken to reach 10% of peak impulse voltage. Similarly, tail time is the difference between the time taken to reach 50% of peak impulse voltage during discharging and time taken to reach 10% of peak impulse voltage during charging. The front time, tail time and peak voltage calculated for all the 8 stages have been formulated below in a table below.

For a standard impulse wave the front time is 1.2µ sec and tail time is 50µ sec and the allowable percentage of error for rise and fall time is 30% and 20%. The front time, tail time and error for the observed results has been tabulated.

To obtain the values of impulse voltage at 10%, 90% and 50% cursor option in the toolbar of Grapher window of Multisim software is used. To use it first the peak value is recorded and according to that its 10%, 90% and 50% is calculated. Then by putting these values the corresponding values on time axis is shown on the graph.

4.2.1: Standard Marx Generator

The values of front time, tail time and error in front time and tail time were calculated following the above procedure. These values were calculated for a total of eight stages and were tabulated. The table for front time, tail time and error calculation is shown below.

TABLE-III

FRONT TIME, TAIL TIME AND ERROR CALCULATION (STANDARD MARX CIRCUIT)

Stage	Front Time (μ second)	Tail Time (μ second)	V_p (volt)	%error in rise time	%error in fall time
1st	0.90	51.3	20.9251	16.66	2.6
2nd	1.00	51.3	30.5160	16.66	2.6
3rd	1.00	51.3	59.8419	16.66	2.6
4th	1.00	51.3	77.1969	16.66	2.6
5th	1.00	51.3	86.0802	27.08	2.6
6th	1.00	51.3	92.6174	16.66	2.6
7th	1.00	51.3	95.0183	16.66	2.6
8th	1.00	51.3	101.8996	16.66	2.6

4.2.2: Improved Marx Generator

The values of front time, tail time and error in front time and tail time were calculated following the above procedure. These values were calculated for a total of eight stages and were tabulated. The table for front time, tail time and error calculation is shown below.

TABLE-IV

FRONT TIME, TAIL TIME AND ERROR CALCULATION (IMPROVED MARX CIRCUIT)

Stage	Front Time (μ second)	Tail Time (μ second)	V_p(Volts)	%error in rise time	%error in fall time
1st	1.125	43.4	293.993	6.25	13.2
2nd	0.500	45.4	304.9673	58.33	9.20
3rd	0.625	45.4	298.0993	47.91	9.20

4th	0.500	45.4	297.1473	58.33	9.20
5th	0.500	44.5	147.045	58.33	11.0
6th	0.500	43.9	280.0826	58.33	12.2
7th	0.625	43.2	274.0896	47.91	13.6
8th	1.250	43.4	268.2800	4.166	13.2

4.3 Energy and Efficiency Calculation

The maximum energy stored was calculated using equation (4)

$$W = ((\frac{C1}{n}) * V_o * V_o)/2 \text{ .... } (4)$$

Where, $C1$ is the charging capacitor; V_o is the applied dc voltage and n is the number of stage. The maximum stored energy within the discharge capacitor C1 is the most important parameter of Marx impulse generators. As C1 is always greater than C2 this parameter determines mainly the cost of generator. Impulse generators are nominally rated by the total voltage (nominal), the number of stages and the gross energy stored. The nominal output voltage is the number of stages multiplied by the charging voltage.
The efficiency of Marx Impulse generator is given by equation (2) and (3)

$$\text{Efficiency} = \frac{Vp}{Vo} \text{ ... . } (2)$$

Where, V_p is the peak output voltage; V_o is the applied DC voltage. It can also be given by

$$\text{Efficiency} = (1/(1 + (C2 \times n)C1)) \times (1/(1 + \left(\frac{R1}{R2}\right)) \text{ .... } (3)$$

Where, $C1, C2$ are charging and discharging capacitors, $R1$, $R2$ Are front and tail resistors and n is the number of stage. This value is always smaller than 1 or 100 percent. The equation (3) yields decrement in efficiency due to an extra term. As the ratio of $R1/R2$ is dependent upon the wave shape, the simple dependency from $C2/C1$ only is lost. For a 1.2/50µs impulse and similar impulse voltages the rapid increase of $R1/R2$ leads to decrease in efficiency for $C2/C1 \leq 0.1$. Thus the efficiency moves through an optimum value and decreases for high $C2/C1$ values as well as for small ones. Very small value of this ratio may even result in failure of circuit.

4.3.1 Standard Marx Generator

The energy of standard Marx Impulse Generator and its efficiency for a total of eight stages were calculated by using the above equations and the resulting values are shown in the table below. The peak voltage was obtained by using the cursor option in Grapher window of Multisim software and the dc voltage output was measured with the help of an indicator.

TABLE-V

ENERGY AND EFFICIENCY CALCULATION (STANDARD MARX CIRCUIT)

Stage	V_p (volt)	Energy (joules)	Efficiency (%)
1st	20.92510	1.0728	80.94
2nd	30.51600	0.6086	84.73
3rd	59.84190	0.4693	82.65
4th	77.19690	0.3209	79.97
5th	86.08020	0.2414	77.19
6th	92.61740	0.1906	74.49
7th	95.01830	0.1522	71.91
8th	101.8996	0.1240	69.46

4.3.2 Improved Marx Impulse Generator

The energy of Improved Marx Impulse Generator and its efficiency for a total of eight stages were calculated by using the above equations and the resulting values are shown in the table below. The peak voltage was obtained by using the cursor option in Grapher window of Multisim software and the dc voltage output was measured with the help of an indicator.

TABLE-VI

ENERGY AND EFFICIENCY CALCULATION (IMPROVED MARX CIRCUIT)

Stage	V_p(Volts)	Energy(joules)	Efficiency (%)
1st	293.9930	1.72860	80.94
2nd	304.9673	0.93005	88.78
3rd	298.0993	0.59242	88.43
4th	297.1473	0.44140	87.24
5th	147.0450	0.08640	75.77
6th	280.0826	0.26148	84.23
7th	274.0896	0.21464	82.65
8th	268.2800	0.17993	81.04

4.4 Comparison of the waveforms obtained from Standard Marx Circuit and Improved Marx Circuit

After the calculation of front time, tail time, percentage error in front time and tail time, maximum stored energy and efficiency for both the Standard as well as Improved Marx impulse Generator a brief comparison in between the two circuits on the basis of generated impulse wave form was made.

Working of both Standard and Improved Marx generator is same the variation lies in the charging and discharging time. The cause being different tail resistors used in the two circuits. In the case of Improved Marx impulse Generator the sphere gap acts as potential divider and it divides the tail resistor thereby resulting in different time constants as compared to the Standard Marx impulse Generator. This in return gives rise to different front time and tail time values.

The comparison is shown between the two impulse waveforms below. The waveforms have been marked separately that are obtained from Standard and Improved Marx Generator.

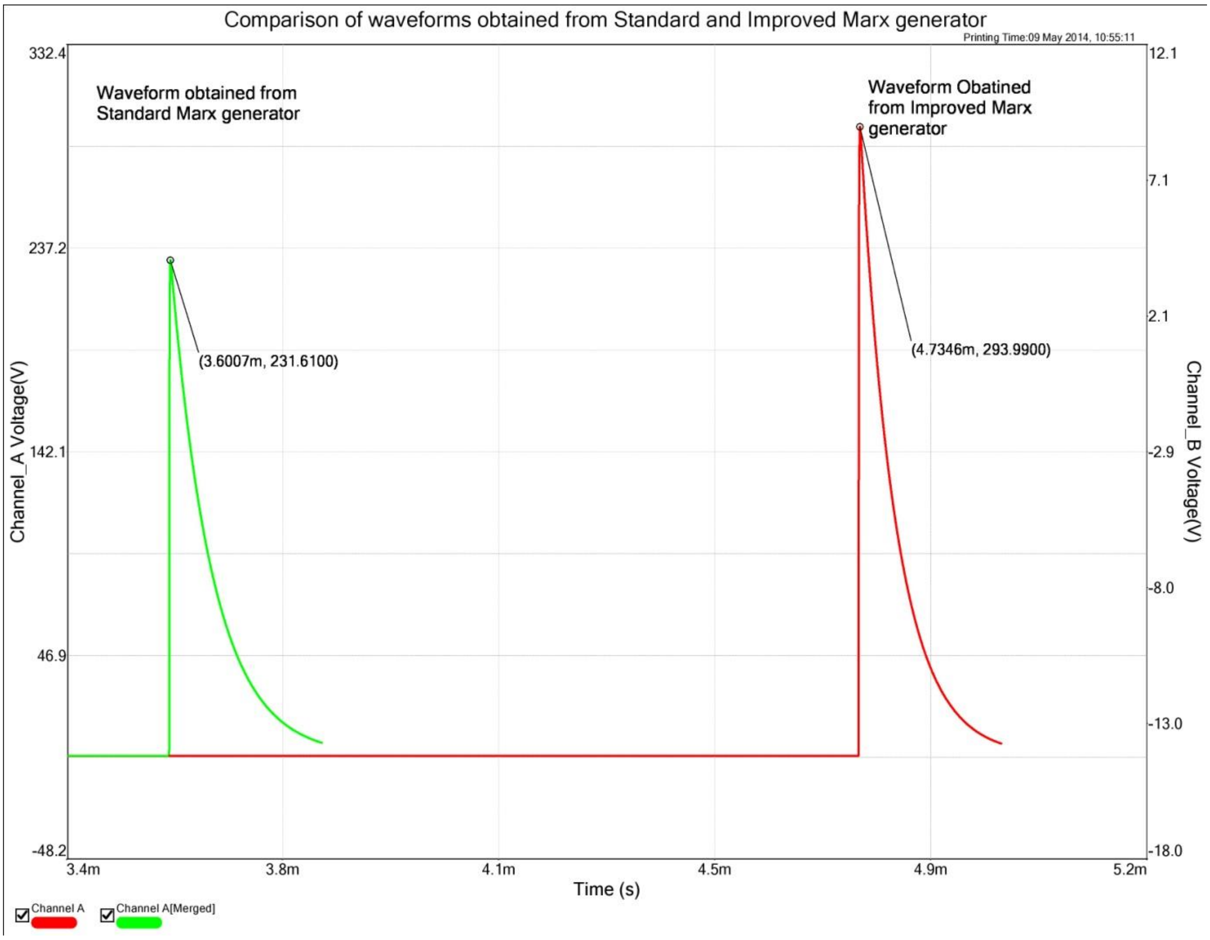

Figure 4.11: Comparison of two curves obtained from Standard Marx Circuit and Improved Marx Circuit. The green curve depicting the waveform of standard Marx circuit and the red one depicting the waveform obtained from Improved Marx circuit.

CHAPTER 5

Practical Experimental Setup for Standard Marx Impulse Generator

Practical Circuit model of two stage standard Marx Generator

Practical Circuit Analysis

CHAPTER 5

PRACTICAL EXPERIMENTAL SETUP FOR STANDARD MARX IMPULSE GENERATOR

5.1 Practical Circuit model of two stage standard Marx Generator

A practical model of two stage circuit was built as shown in Figure 5.1. A step down transformer of 230V/12V, 5mA was used. A 230 V supply is given to the transformer which step downs to 12 V. The circuit consists of charging capacitor C1 and C3 of 10µF, discharging capacitor C2 of 0.5µF and wave shaping resistors R1 0.88Ω and R2 12.107Ω.

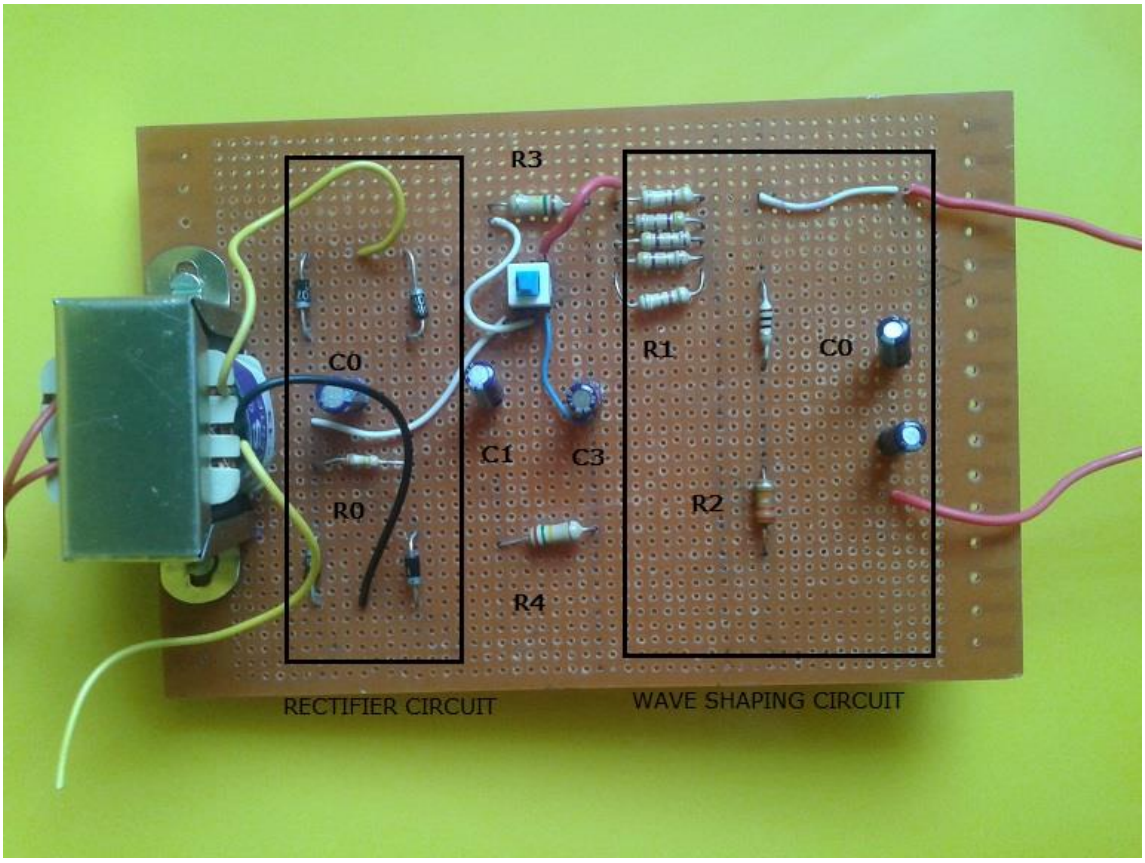

Figure 5.1: Practical circuit setup of second stage Marx Impulse voltage Generator

Due to unavailability of resistors less than 1Ω the wave shaping resistor R1 was approximated to 1Ω. Five resistors of 5Ω each were connected in parallel to get a resultant of 1Ω. A resistor of 10Ω and 2.2Ω each were connected in series to get a approximate resultant of 12.107Ω. Two 1μF capacitors were connected to give the discharging resistor C2.

The resistor values are chosen such that the charging period should be less within 1 minute. The wave shaping resistors can be connected external to the general circuit. For large impulse generators the impulse wave shaping also depends on the test object value (resistance, inductance and capacitance of test object). The gap spacing of all the sphere gaps should be same for correct operation. Generally the sphere gaps are fixed along an insulating rod so that the spacing can be adjusted as per requirement. Impulse voltage magnitude is not dependent in case of a controlled operation but gap spacing do matters in uncontrolled operation. For the same gap spacing a certain range of impulse voltage is generated for controlled impulse generator. In this circuit sphere gap is replaced by six pin switch which is having two NO contact and two NC contact. For the second stage two out of the six NO and NC contacts were used.

As discussed earlier in introduction part, the complete Max impulse generator has been divided in two parts. The first part is generated through a rectifier circuit and the second part is the Marx circuit whose setup determines the wave shape of the impulse wave. From the operation of these two parts we obtain the lightening voltage as an output.

The practical circuit that was designed has these two parts identified and marked in the Figure 5.1. Rectifier circuit and wave shaping circuits are indicated by the rectangular portion of the circuit. The diodes used in the rectifier circuit were IN4007. This circuit rectifies 12 V AC to 19.2 V DC which is then supplied to Marx generator circuit. This charging voltage helps in charging the capacitors parallel and after this switch is closed it is discharged in series through R1 and R2.

5.2 Practical Circuit Analysis

5.2.1 Two stage Marx Generator circuit

Referring to Figure 5.1, the circuit arrangement consists of a source, transformer, a rectifier circuit and the impulse generating circuit (Marx circuit), test object. The source supplies ac voltage to the transformer, the transformer is a step down transformer which steps down the voltage normally in Volt range as per requirement. The output voltage from the transformer is given as an input to the rectifier circuit. The rectifier circuit converts the ac voltage produced by the transformer to a dc value. The output of the rectifier circuit is give to the ipulse generating circuit where all the capacitors are charged in parallel to the rectifier's output voltage and then discharged in series giving voltage output that is several times more than the output voltage of the rectifier output voltage. This depends on the number of stages involved in the impulse circuit. The charging capacitors (C1& C3) are charged using the transformer supply. Then the six pin switch is turned off to discharge both the capacitors (C1& C3) in series through the wave shaping circuit and discharging capacitor (C2).

The impulse voltage waveform across the capacitor C2 is observed using digital oscilloscope as shown in Figure 5.2. Then the value of front time, tail time and peak impulse voltage are calculated by changing the position of the curser in the digital oscilloscope to 10%, 90% and 50% of the peak impulse voltage level. For determining the peak voltage the cursor type was set to amplitude type and for the determining the front time and tail time the cursor type was changed to time.

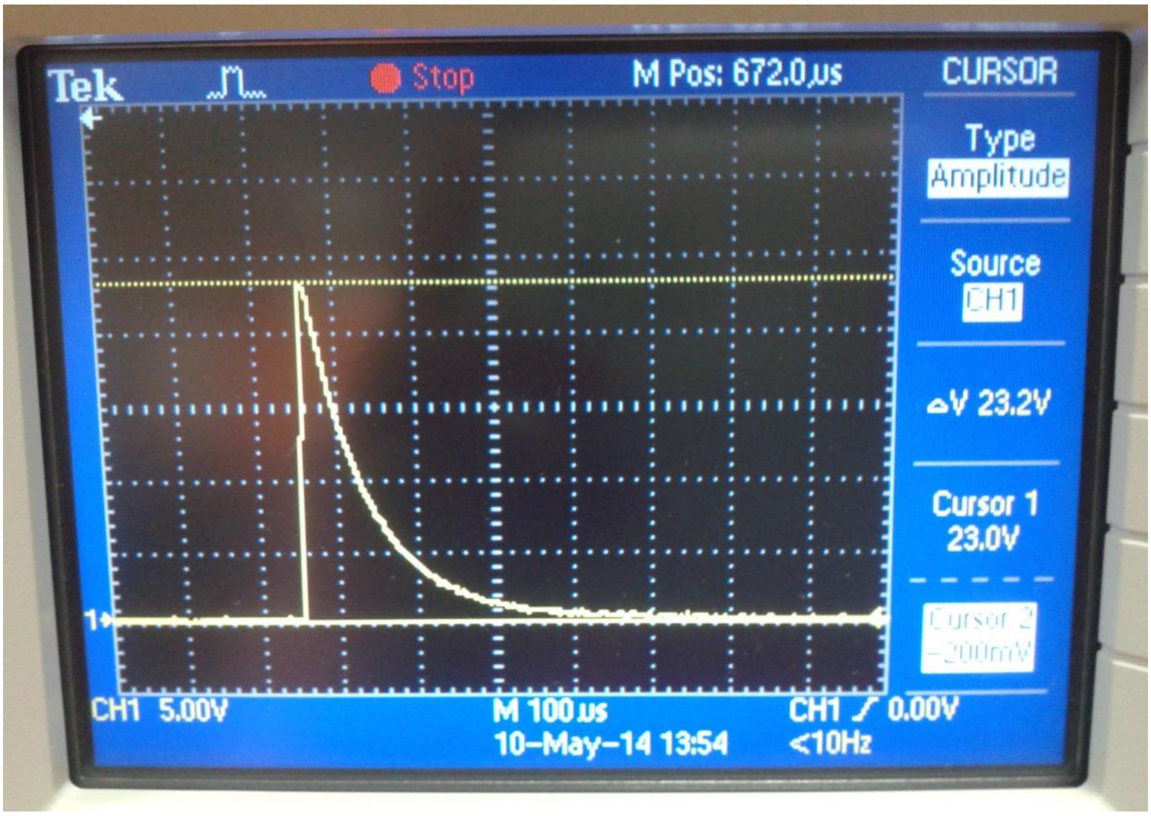

Figure 5.2: Impulse wave of second stage Marx impulse Voltage Generator obtained from CRO

It was observed that with a charging voltage of around 19 V at each stage the output obtained is less than the desired value. The peak voltage output of the second stage Standard Marx Impulse generator was found to be 23.2 V as shown in the Figure 5.2.

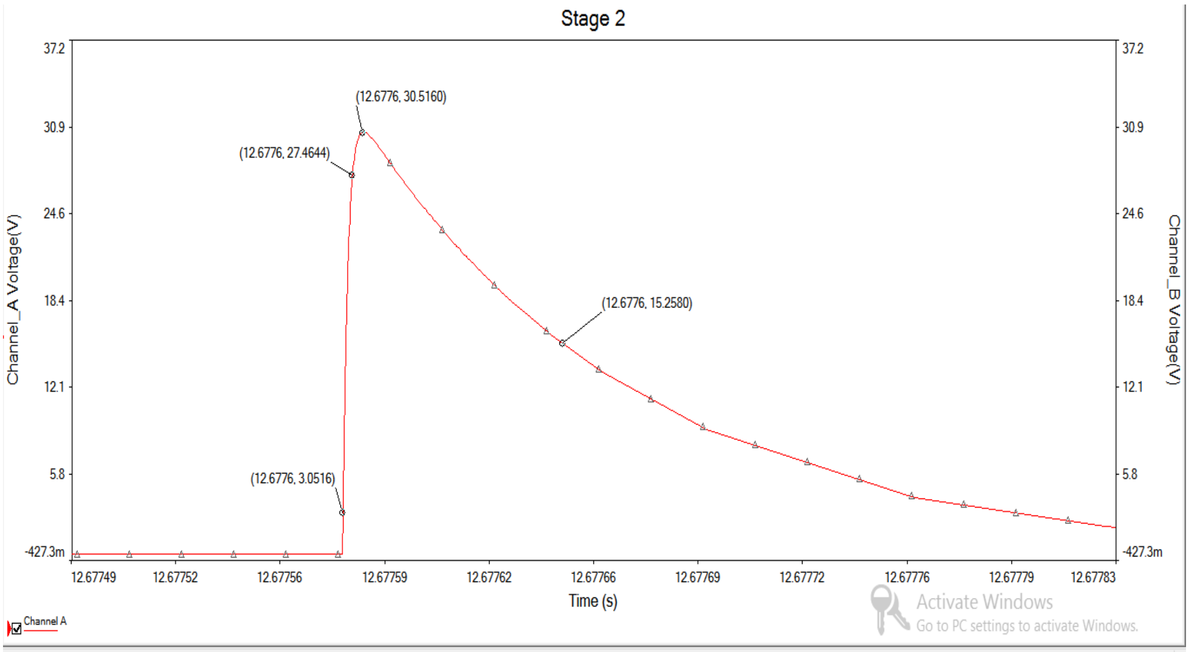

Figure 5.3: Impulse wave obtained from Multisim for second stage Marx Impulse voltage Generator

In the second stage of Standard Marx impulse voltage dc charging voltage of 18V in each stage was applied and hence a total of 36V was applied to the Marx generator. But the output obtained is 30.5160V which is less than the desired value.

In both practical as well as simulated circuit it was found that the desired output voltage was not obtained. This error occurs due to insufficient charging of the charging capacitor. This insufficient charging occurs due to the presence of series resistors. After the results obtained in both the simulated as well as practical Marx impulse generator a comparison on impulse wave parameters like peak voltage V_p, rise time, fall time and error in rise time and fall time was carried out. The comparison was carried out in order to observe to what extent the values obtained in simulation and that obtained in practical circuit operation correlate. The methods to determine the peak voltage, rise time and fall time in practical as well as simulated Standard Marx impulse voltage has been discussed earlier and following the procedure listed there the values obtained were recorded and tabulated.

The table for comparison between the simulated and practical Marx generator is given below.

TABLE-VII

COMPARISON OF RESULTS OBTAINED FROM SIMULATED CIRCUIT AND PRACTICAL CIRCUIT

Simulated circuit Results						Practical circuit Results				
Stage	V_p (Volts)	Rise time(μs)	Fall time(μs)	Error in rise time %	Error in fall time %	V_p (Volts)	Rise time (μs)	Fall time (μs)	Error in rise time %	Error in fall time %
2^{nd}	30.51	1	51.3	16.66	2.6	23.2	1.7	60	41.66	20

The data is collected in both the cases and the waveforms are plotted which are shown in Figure 5.2 and 5.3. The values obtained from simulated circuit and practical circuit are different because of the capacitors and resistors used. The tolerances level of resistors used in practical circuit are different from those used in Multisim and the maximum charging voltages in both practical and simulation aren't the same. Moreover the connection of resistors and capacitors in parallel and series gives an approximate value of what is exactly used in simulation also adds to the errors. Due to these parameters differences have resulted in the two circuits. The ripples produced in the rectifier circuit also contribute in the errors.

In practice all the capacitors are not charged to the same value due to the presence of series resistance in the circuit. In theory any desired output voltage can be obtained simply by increasing the number of stages. But in practise the effect of series resistance between the source and distant capacitor limits the voltage obtainable.

CHAPTER 6

Conclusions

CHAPTER 6

CONCLUSIONS

A small scale of generation of high impulse voltage is implemented in the simulation with the NI Multisim software environment. It is found that the overall simulated result is close to standard impulse generator 1.2 / 50 µs wave shape for all the stages of Marx generator. The ratio of C1/C2 is taken as 20 in each stage and the impulse waveform was governed by the values of front resistor and tail resistor. The energy and efficiency at each step was calculated and was tabulated. For simulation the sphere gap is replaced with a simple switch in Multisim Software. A practical Marx impulse circuit of second stage was built and the results obtained from it were compared with that obtained in simulation.

The values from practical and simulated waveforms in the fields of rise time, tail time, peak voltage and error in rise time and tail time have a considerable amount of difference Shown in Table VII. As explained in Chapter 5, the difference is caused by a number of factors. The prime reason is the difference in the charging resistors and capacitors used in the simulation and practical circuit. The tolerances level of resistors used in practical circuit are different from those used in Multisim and the maximum charging voltages in both practical and simulation aren't the same. Moreover the connection of resistors and capacitors in parallel and series gives an approximate value of what is exactly used in simulation also adds to the errors. Due to these parameters differences have resulted in the two circuits. In practice all the capacitors are not charged to the same value due to the presence of series resistance in the circuit as the series resistance between the source and distant capacitor limits the voltage obtainable.

In this work, the entire circuit is modelled, simulated and practically designed in two different parts one from source to rectifier consists of the first part and the impulse Marx circuit forms the second part. The effects of the circuit parameters on the impulse wave characteristics is also studied and it is found that as long as the proper parameter selection is made the circuit will produce the standard waveform from the Standard as well as Improved Marx Impulse voltage generator.

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